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We report on a detailed analysis of the superconducting properties of boron-doped silicon films grown along the 001 direction by gas immersion laser doping. This technique is proved to be a powerful technique to dope silicon in the alloying range 2–10 at.% where superconductivity occurs. The superconducting transitions are sharp and well defined both in resistivity and magnetic susceptibility. The variation of T_c on the boron concentration is in contradiction with a classical exponential dependence on superconducting parameters. Electrical measurements were performed in magnetic field on the sample with $c_B = 8$ at.% (400 laser shots) which has the highest T_c (0.6 K). No hysteresis was found for the transitions in magnetic field, which is characteristic of a type-II superconductor. The corresponding upper critical field was on the order of 1000 G at low temperatures, much smaller than the value previously reported. The temperature dependence of H_{c2} is very well reproduced by the linearized Gorkov equations neglecting spin effects in the very dirty limit. These measurements in magnetic field allow an estimation of the electronic mean-free path, the coherence length, and the London penetration depth within a simple two-band free electron model.

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1. Introduction

Superconducting doped semiconductors have recently attracted a lot of interest (see [1] for a review). Among them silicon [2] is a special case as it is the technologically most important material and microelectronics processes could be applied to design new all-silicon hybrid (semiconducting-metallic-superconducting) devices.

To shed light on the interplay between disorder-induced localization, Coulomb interaction and superconductivity, we present here a systematic study of the evolution of the superconducting transition temperature as a function of boron doping in silicon.

2. Experimental

Thin films of boron doped silicon have been prepared by gas-immersion laser doping [3, 4]. The surface of a silicon wafer is melted using laser pulses in the presence of a chemisorbed BCl_3 gas. Boron diffuses into the liquid and is incorporated in the crystal upon cooling and recrystallization after the laser pulse (20–60 ns). This technique allows to exceed the solubility limit and to reach a boron content in the range 2–10 at.%. The superconducting transition temperatures were determined from electrical resistivity measurements in a 4-contact geometry and from ac magnetic susceptibility experiments [5]. Quantitative determination of boron concentrations c_B were made by an isotopic comparative analysis of secondary ion mass spectroscopy (SIMS) profiles [6].

3. Results

Figure 1 represents the dependence of T_c on the boron content in a series of films with c_B ranging between 2 and 4 at.%. Above 4 at.% we observed previously [5] a non-intrinsic saturation of T_c probably related to a non-substitutional incorporation of boron. In the range of doping explored here, T_c is a quasi-linear function of c_B instead of the power law dependence, $T_c \propto (c_B/c_C - 1)^{0.5}$, c_C being a critical concentration, found previously not only in doped silicon [5] but also in doped diamond [7]. As a comparison the standard McMillan formula, $T_c \propto \exp(-1/[\lambda_{e-p}/(1+\lambda_{e-p}) - \mu^*])$ is reported in Fig. 1 with the Coulomb pseudopotential μ^* set equal to 0 (BCS limit) and 0.1 (typical value in metals). The electron–phonon coupling constant λ_{e-p} has been extrapolated linearly from virtual crystal approximation (VCA) calculations [8]. A free electron model with $\lambda_{e-p} \propto$ density of states $N(E_F) \propto c_B^{1/3}$ also fails to explain the data.

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The smooth decay of T_c cannot be reproduced by any exponential dependence on superconducting parameters.

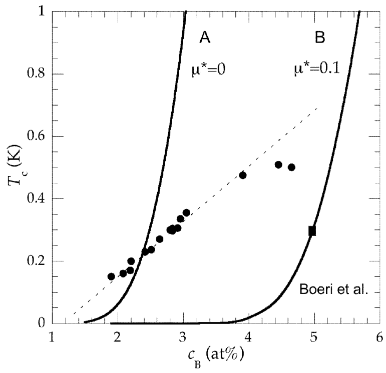

Fig. 1. Dependence of the superconducting transition temperature T_c on doping. The full lines are values obtained by the McMillan formula with the e–phonon coupling estimated by VCA approach, the Coulomb pseudopotential μ^* being equal to 0 (respectively 0.1) in line A (respectively B). The broken line is a linear fit for $2 < c_B < 4$ at.%.

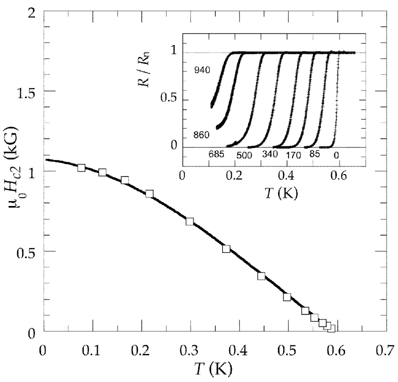

Fig. 2. Temperature dependence of the upper critical field. Full line is a fit by classical theory in the dirty limit. In the inset: temperature variation of the electrical resistance normalized to its normal state value in various magnetic fields given in G. The upper critical field was defined by the criterion where the ratio $R/R_n = 0.9$.

In Fig. 2 we present the temperature dependence of the upper critical field H_{c2} deduced from resistivity measurements at various fixed magnetic fields performed on the sample with $c_B = 8$ at.% (400 laser shots) which has the highest T_c (0.6 K). The transitions remained sharp as the magnetic field was increased and no hysteresis was observed which is consistent with a second-order transition and doped silicon being a type-II superconductor. The standard microscopic theory neglecting paramagnetic limitation reproduces the data very well (see full line in Fig. 2). Within a simple two-band free electron model one obtains an electronic mean free path $l \approx 2$–3 nm, a coherence length $\xi \approx 1000$ nm, and a London penetration depth $\lambda \approx 60$ nm. Comparing this λ with the thickness, 80 nm, of these films, we come to the conclusion that we might be in a quasi-2D regime.

4. Conclusions

Doped silicon should be intrinsically a type-I superconductor, $\kappa = \lambda/\xi \approx 1/15 \ll 1$, but is turned into a type-II system by strong impurity effects [9].

The variation of T_c is in contradiction with a classical exponential dependence on superconducting parameters. Instead, T_c increases linearly with boron content raising the question of the importance of disorder and/or dimensionality.

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